

## Final Technical Report

**Project Title: "Chondritic Meteorites: Nebular and Parent-Body Formation Process"**

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### WORK STATEMENT

#### Introduction

Chondritic meteorites are the products of condensation, agglomeration and accretion of material in the solar nebula; these objects are the best sources of information regarding processes occurring during the early history of the solar system. We obtain large amounts of high-quality chemical and petrographic data and use them to infer chemical fractionation processes that occurred in the solar nebula and on meteorite parent bodies during thermal metamorphism, shock metamorphism and aqueous alteration. We compare diverse groups of chondrites and model their different properties in terms of processes that differed at different nebular locations or on different parent-bodies. In order to expand our set of geochemically important elements (particularly Si, C, P and S) and to distinguish the different oxidation states of Fe, Greg Kallemeyn spent three months (1 Sept. - 30 Nov. 1995) at the Smithsonian Institution to learn Eugene Jarosewich's wet chemical techniques. Key specimens from the recently established CK, CR and R chondrite groups were analyzed.

#### Nebular diversity recorded in chondritic meteorites

Our chief goal is to gather compositional information, which can be used to test models of chondrite (and planet) formation. We are particularly interested in examining the bulk compositions of unusual groups or grouplets of chondrites in order to learn about time-space variations in nebular conditions and processes. We have recently published comprehensive studies of CK (Kallemeyn et al., 1991) and CR chondrites (Kallemeyn et al., 1994) as well as the new carbonaceous chondrite grouplet consisting of Coolidge (formerly misclassified CV) and Loongana 001 (Kallemeyn and Rubin, 1995). We have a paper in press (Kallemeyn et al., 1996) describing our comprehensive chemical-petrographic study of the new R chondrite group (formerly known as Carlisle-Lakes-like chondrites); this group does not belong to the ordinary, enstatite or carbonaceous chondrite classes. Greg Kallemeyn has recently co-authored a paper (Weisberg et al., 1996) describing detailed mineralogical/petrological/analytical/isotopic studies of the Kakangari chondrite grouplet (i.e., Kakangari; Lea County 002; LEW87232).

Because meteorite researchers lack the field information so important to terrestrial petrologists, it is essential that we obtain large amounts of high-quality data on the set of samples that nature provides. The more data that become available on diverse classes of chondrites, the more likely it is that we will recognize patterns of nebular processes, location-dependent differences in conditions, and/or the signatures of different batches of presolar matter. In addition, more detailed information increases our ability to distinguish between nebular and metamorphic effects -- a major problem that has even spawned a conference to be held in conjunction with the 1997 Meteoritical Society meeting. Even the least-altered

chondrites experienced mild-to-moderate heating and/or shock during the compaction that made rocks out of the porous assemblages that agglomerated in the nebula.

There is a broad consensus that the differences in chondritic bulk chemical and isotopic compositions reflect differences in nebular processes that differed in space and time. Because many more kinds of chondrites probably were formed in the nebula than have been characterized to date, it is quite likely that our meteorite collections represent a poorly sampled continuum. It is probable that most chondrites in our collections were formed in the asteroid belt between 2.2 and 3.5 AU from the Sun, but it seems plausible that chondritic planetesimals also formed beyond either of these extremes. It is essential to search for evidence that helps test this hypothesis. Information that might offer clues regarding the distance from the Sun at which these materials formed include the  $\text{FeO}/(\text{FeO} + \text{MgO})$  ratios and the O-isotope composition of low-temperature nebular components. Below are research projects directed toward the diversity of chondritic materials that we plan to carry out during the next two years:

### 1. ALH85085 and congeners -- the "CH" carbonaceous "chondrite" group

Allan Hills 85085 is the prototype of a very unusual group of meteorites. These rocks contain chondrules and other common constituents of chondrites, but have anomalous compositions and phase abundances. Specifically, they are characterized by very high siderophile abundances (e.g.,  $\text{Fe}/\text{Si} = 1.7 \times \text{solar}$ ), low volatile abundances (e.g.,  $\text{Na}/\text{Si} = 0.25 \times \text{solar}$ ;  $\text{S}/\text{Si} = 0.03 \times \text{solar}$ ), numerous microchondrules and tiny refractory inclusions (many containing Ca dialuminate). Many phyllosilicate-rich, chondrule-free clasts, petrographically similar to CI chondrites, are also present. Since ALH85085 was first described (Grossman et al., 1988; Weisberg et al., 1988; Scott, 1988), several more Antarctic and one Saharan meteorite (PCA91467, RKP92435, PAT91546, Acfer 182) have been recovered that are clearly related to ALH85085. Although Acfer 182 has been described and analyzed by neutron activation (Bischoff et al., 1993), the Antarctic samples remain unanalyzed and incompletely described. If this unique group formed in the solar nebula, it extends the range of previously known metal/silicate fractionation effects by a factor of  $\sim 2$ . We propose to complete a comprehensive trace-element/petrographic study of these meteorites and compare their bulk compositions to those of other chondrite groups. These data are essential in evaluating whether the original nebular models of are more (or less) viable than the parent-body model of Wasson and Kallemeyn (1990).

### 2. Investigation of new and exotic chondrites

Within the next two years we expect to submit for publication studies of several sets of unusual chondrites that we have already analyzed by neutron activation but have not yet studied petrographically. We intend to also determine major elements (i.e., Si, P, S, C) in these samples by Jarosewich's wet-chemical techniques after setting up the appropriate facilities at UCLA. The meteorites include: **(a) MAC87300, MAC877301 and MAC88107** -- chondrites that contain abundant phyllosilicates and small chondrules (Browning et al., 1991; Zolensky, 1991) like CM2 chondrites, but unlike CM2 chondrites, have no detectable natural or induced thermoluminescence (TL) (Sears et al., 1990). Preliminary INAA data (Kallemeyn, 1992, 1993) indicate that these chondrites are distinct from CM chondrites in having lower abundances of moderately volatile lithophiles, volatile siderophiles and chalcophiles. Sears et

al. (1990) suggested that MAC87300 and MAC88107 were related to the highly unequilibrated CO chondrites, Colony and ALHA77307, because of their unusual TL properties. However, the abundances of volatile siderophiles and chalcophiles in MAC87300 and congeners appear to be higher than in CO chondrites (Kallemeyn, 1993). **(b) Y-82162 and Y-86720** -- CI-like chondrites. **(c) Belgica7904** -- a unique carbonaceous chondrite. **(d) Deakin 001** -- a unique OC-like chondrite with high  $\delta^{18}\text{O}$  (Bevan and Binns, 1989).

In addition, we are alert to the reports of new chondrites recovered from Antarctica, the Nullarbor Plain of Australia and the Sahara Desert, and request samples of all potentially exotic materials for INAA and petrographic study.

#### Reinvestigation of EH and EL enstatite chondrites

Since Kallemeyn and Wasson (1986) last completed a comprehensive INAA study of the enstatite chondrites, the number of these meteorites has proliferated. There are now petrographically well-characterized EL3 and EL5 chondrites which were unknown in 1986. One of the most fascinating aspects of the 1986 study was the discovery that EL6 chondrites have a fractionated rare-earth-element (REE) pattern (mean Mg- and CI-normalized La/Sm = 0.88), the first ever found for a chondrite group. Because of the recent recognition of EL3 and EL5 chondrites, it is important to ascertain if the REE fractionation is characteristic of all EL metamorphic grades. Recently, Zhang et al. (1995) analyzed a number of enstatite chondrites (including many Antarctic samples) by INAA and failed to find evidence of REE fractionation. Although the scatter in their data suggests appreciably lower precision than that of the UCLA data, it is important to confirm if EL chondrites have fractionated REE patterns.

Another recent development in the understanding of enstatite chondrites is the interpretation by Rubin and Scott (1996) that many EH chondrites (particularly Abee, Adhi Kot and RKPA80259) are impact-melt breccias; furthermore, Rubin et al. (1996) suggested that some EL chondrites (e.g., Blithfield) are annealed impact-melt breccias. A prime motivation of gathering new compositional data on enstatite chondrites is to determine what compositional effects (e.g., depletion in siderophiles and chalcophiles due to partial separation of a metal-sulfide liquid) may plausibly be attributed to shock melting. For example, among EH chondrites, Abee and Adhi Kot can be compared to Parsa, which Rubin et al. (1996) found to be one of the least-shocked EH3 chondrites (despite the occurrence of a large impact-melt-rock clast inside it). Among EL chondrites, Blithfield can be compared to LEW88714 and Pillistfer which are unbrecciated and show no evidence of post-shock annealing.

#### Support of research on lunar samples, martian meteorites and program-relevant terrestrial geochemical problems

This NASA grant provides key funds to maintain our INAA lab. This lab is used not only for the chondrite research described above but also for neutron-activation studies of lunar samples, achondrites and program-relevant terrestrial problems. For example, Paul Warren (UCLA) uses these facilities to study lunar and martian meteorites, and to identify pristine rocks and primary partial melts among Apollo samples. Frank Kyte (UCLA) uses the lab to investigate the nature and distribution of ejecta from the KT impact event and to search for enhanced concentrations of Ir and other noble metals at stratigraphic boundary layers associated with other mass extinctions.

## References

- Bevan A. W. R. and Binns R. A. (1989) Meteorites from the Nullarbor Region, Western Australia: II. Recovery and classification of 34 new meteorite finds from the Mundrabilla, Forrest, Reid and Deakin areas. *Meteoritics* **24**, 135-141.
- Bischoff A., Palme H., Schultz L., Weber D., Weber H. W. and Spettel B. (1993) Acfer 182 and paired samples, an iron-rich carbonaceous chondrite: Similarities with ALH 85085 and relationship to CR chondrites. *Geochim. Cosmochim. Acta* **57**, 2631-2648.
- Browning L., Zolensky M. E. and Barrett R. (1991) Serpentine and modal compositions of CM chondrites (abstract). *Lunar Planet. Sci.* **22**, 145-146.
- Grossman J. N., Rubin A. E. and MacPherson G. J. (1988) ALH85085: A unique volatile-poor carbonaceous chondrite with possible implications for nebular fractionation processes. *Earth Planet. Sci. Lett.* **91**, 33-54.
- Kallemeyn G. W. (1992) Three ungrouped carbonaceous chondrites from MacAlpine Hills, Antarctica (abstract). *Lunar Planet. Sci.* **23**, 649-650.
- Kallemeyn G. W. (1993) A carbonaceous chondrite grouplet from Macalpine Hills, Antarctica (abstract). *Symp. Antarc. Met.*, 91-92.
- Kallemeyn G. W. (1994) Compositional study of Kakangari and LEW 87232 (abstract). *Meteoritics* **29**, 479-480.
- Kallemeyn G. W. and Rubin A. E. (1995) Coolidge and Loongana 001: A new carbonaceous chondrite grouplet. *Meteoritics* **30**, 20-27.
- Kallemeyn G. W., Rubin A. E. and Wasson J.T. (1996) The compositional classification of chondrites: VII. The Rumuruti (R) chondrite group. *Geochim. Cosmochim. Acta* **60**, in press.
- Kallemeyn G. W. and Wasson J. T. (1986) Compositions of enstatite (EH3, EH4,5 and EL6) chondrites: Implications regarding their formation. *Geochim. Cosmochim. Acta* **50**, 2153-2164.
- Kallemeyn G. W., Rubin A. E. and Wasson J. T. (1991) The compositional classification of chondrites: V. The Karoonda (CK) group of carbonaceous chondrites. *Geochim. Cosmochim. Acta* **55**, 881-892.
- Kallemeyn G. W., Rubin A. E. and Wasson J. T. (1994) The compositional classification of chondrites: VI. The CR carbonaceous chondrite group. *Geochim. Cosmochim. Acta* **58**, 2873-2888.
- Rubin A.E., and Scott E.R.D. (1996) Abee and related EH chondrite impact-melt breccias. *Geochim. Cosmochim. Acta*, submitted.
- Rubin A. E., Scott E. R. D. and Keil K. (1996) Shock metamorphism of enstatite chondrites. *Geochim. Cosmochim. Acta*, submitted.
- Scott E. R. D. (1988) A new kind of primitive chondrite, Allan Hills 85085. *Earth Planet. Sci. Lett.* **91**, 1-18.
- Sears D. W. G., Sears H. and Myers B. M. (1990) The natural TL survey of the 1987/1988 Antarctic meteorite collections: Pairing, an unusual carbonaceous chondrite group and the lunar meteorites (abstract). *Lunar Planet. Sci.* **21**, 1121-1122.
- Wasson J. T. and Kallemeyn G. W. (1990) Allan Hills 85085: a subchondritic meteorite of mixed nebular and regolithic heritage. *Earth Planet. Sci. Lett.* **101**, 148-161.
- Weisberg M. K., Prinz M. and Nehru C. E. (1988) Petrology of ALH85085: A chondrite with unique characteristics. *Earth Planet. Sci. Lett.* **91**, 19-32.
- Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Grady M. M., Franchi I., Pillinger C.T. and Kallemeyn G.W. (1996) The K (Kakangari) chondrite grouplet. *Geochim. Cosmochim. Acta*, submitted.
- Zhang Y., Benoit P. H. and Sears D. W. G. (1995) The classification and complex thermal history of the enstatite chondrites. *J. Geophys. Res.-- Planets* **100**, 9417-9438.
- Zolensky M. E. (1991) Mineralogy and matrix composition of "CR" chondrites Renazzo and EET 87770, and ungrouped chondrites Essebi and MAC 87300 (abstract). *Meteoritics* **26**, 414.

## Scientific Personnel

G.W. Kallemeyn and A. E. Rubin were supported on this grant

## Administrative Matters

Due to NASA reorganization, the second year funding of this research was processed through Goddard Space Flight Center under the new grant NAG5-4766.

## Patents or Inventions Result

None

### PUBLICATIONS: Papers published 1993-1996:

- WASSON J.T., RUBIN A.E. and KALLEMEYN G.W. (1993) Reduction during metamorphism of four ordinary chondrites. *Geochim. Cosmochim. Acta* 57, 1865-1878.
- RUBIN A.E. and MITTFELDELDT D.W. (1993) Evolutionary history of the mesosiderite asteroid: A chronologic and petrologic synthesis. *Icarus* 101, 201-212.
- RUBIN A.E. and KALLEMEYN G.W. (1993) Compositional studies of antarctic meteorites. *Ant. J. U.S.* 28, 56-57.
- RUBIN A.E. (1993) Magnetite-sulfide chondrules and nodules in CK carbonaceous chondrites: Implications for the timing of CK oxidation. *Meteoritics* 28, 130-135.
- WARREN P.H. and KALLEMEYN G.W. (1993) The ferroan-anorthositic suite, the extent of primordial lunar melting, and the bulk composition of the Moon. *J. Geophys. Res.* 98, 5445-5455.
- WARREN P.H. AND KALLEMEYN G.W. (1993) Geochemical investigation of two lunar mare meteorites. *Proc. NIPR Symp. Antarctic Meteorites* 6, 35-57.
- KALLEMEYN G.W. (1993) Neutron activation analysis in *Advances in Analytical Geochemistry*. (M. Hyman and M. Rowe, eds.) JAI Press, 193-209.
- KROT A. N., RUBIN A. E., and KONONKOVA N. N. (1993) First occurrence of pyrophanite ( $\text{MnTiO}_3$ ) and baddeleyite ( $\text{ZrO}_2$ ) in an ordinary chondrule. *Meteoritics* 28, 232-239.
- RUBIN A.E. (1994) Metallic copper in ordinary chondrites. *Meteoritics* 29, 93-98.
- SCOTT E.R.D., JONES R.H. and RUBIN A.E.. (1994) Classification, metamorphic history and pre-metamorphic composition of chondrules. *Geochim. Cosmochim. Acta* 58, 1203-1209.
- RUBIN A.E. and KALLEMEYN G.W. (1994) Pecora Escarpment 91002: A member of the new Rumuruti (R) chondrite group. *Meteoritics* 29, 255-264.
- KALLEMEYN G.W., RUBIN A.E. and WASSON J.T. (1994) The compositional classification of chondrites VI. The CR carbonaceous chondrite group. *Geochim. Cosmochim. Acta* 58, 2873-2888.
- RUBIN A.E. (1994) Euhedral metallic Fe-Ni in the Jelica meteorite and other extraterrestrial materials. *Mineral. Mag.* 58, 215-221.
- WASSON J.T., KALLEMEYN G.W. and RUBIN A.E. (1994) Equilibration temperatures of EL chondrites: A major downward revision in the ferrosilite contents of enstatite. *Meteoritics* 29, 658-662.
- RUBIN A.E. and KALLEMEYN G.W. (1994) Compositional studies of new groups of chondritic meteorites. *Ant. J. U.S.* 29, 50-51.
- KROT A.N. and RUBIN A.E. (1994) Glassy chondrules in ordinary chondrites. *Meteoritics* 29, 697-706.
- KALLEMEYN G.W. and RUBIN A.E. (1995) Coolidge and Loongana 001: A new carbonaceous chondrite grouplet. *Meteoritics* 30, 20-27.
- RUBIN A.E. (1995) Petrologic evidence for collisional heating of chondritic asteroids. *Icarus* 113, 156-167.
- WASSON J.T., KROT A.N., LEE M.S. and RUBIN A.E. (1995) Compound chondrules. *Geochim. Cosmochim. Acta* 59, 1847-1869.
- RUBIN A.E. (1995) Fractionation of refractory siderophile elements in metal from the Rose City meteorite. *Meteoritics* 30, 412-417.
- RASMUSSEN K.L., CLAUSEN H.B. and KALLEMEYN G.W. (1995) No iridium anomaly after the 1908 Tunguska impact: Evidence from a Greenland ice core. *Meteoritics* 30, 634-638.

- RUBIN A.E. and KROT A.N. (1996) Multiple heating of chondrules. In *Chondrules and the Protoplanetary Disk*. (ed. by R.H. Hewins, R.H. Jones and E.R.D. Scott), Cambridge University Press, 173-180.
- KROT A.N. and RUBIN A.E. (1996) Microchondrule-bearing chondrule rims: Constraints on chondrule formation. In *Chondrules and the Protoplanetary Disk*. (ed. by R.H. Hewins, R.H. Jones and E.R.D. Scott), Cambridge University Press, 181-184.
- RYDER G., DELANO J.W., WARREN P.H., KALLEMEYN G.W. and DALRYMPLE G.B. (1996) A glass spherule of questionable impact origin from the Apollo 15 landing site: Unique target mare basalt. *Geochim. Cosmochim. Acta* **60**, 693-710.
- WARREN P.H. and KALLEMEYN G.W. (1996) Siderophile trace elements in ALH84001, other SNC meteorites and eucrites: Evidence of heterogeneity, possibly time-linked, in the mantle of Mars. *Met. Planet. Sci.* **31**, 97-105.